Greenhouse Gas Emission Trends and Projections for Missouri, 1990-2015 Technical Report

Chapter 5

Greenhouse Gas Emissions from "Other" Sources – Trends and Projections

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The leading source of greenhouse gas emissions in Missouri, as in other states, is combustion of fossil fuels for energy. Chapters 2 through 4 estimated CO_2 emissions from this source. Fossil fuel combustion accounted for about 75 percent of Missouri's anthropogenic greenhouse gas emissions in 1990. This chapter discusses the sources for the other 25 percent of emissions. In 1990, these "other" sources emitted a total of about 36.8 million tons (STCDE) of greenhouse gas emissions, consisting of about 11.7 million tons of CO_2, 16.7 million tons (STCDE) of methane (CH_4), 3.8 million tons (STCDE) of nitrous oxide (N_2O) and 4.6 million tons (STCDE) of perfluorinated carbons (PFCs).[1]

Under the scenarios developed for this study, the share of these sources in total greenhouse gas emissions is projected to decline. A decline in their share is projected to occur due to a projected 2.5 million ton (STCDE) decrease in total emissions from these sources as well as projected increases in CO_2 emissions from fossil fuel combustion.

Part 1 of this chapter discusses and estimates CO_2 emissions from sources other than fossil fuel combustion. Following the *1990 Inventory*, four sources of CO_2 emissions are covered here: land use changes, which accounted for about 3.6 percent of CO_2 emissions in 1990; industrial and agricultural uses of limestone, which accounted for 3.6 percent; and two sources related to fossil fuel use (non-energy use of fossil fuels, and oxidation of carbon monoxide) which each accounted for just over 1 percent of CO_2 emissions in 1990. Their combined 9.5 percent share of CO_2 emissions in 1990 is projected to decline to less than 8 percent by 2015, increasing the role of fossil fuel combustion as a source of CO_2 emissions in Missouri.

The remainder of the chapter discusses and estimates statewide emissions of three other greenhouse gases. Part 2 estimates trends and projections for methane (CH_4) emissions. In the 1990 baseline year, livestock operations emitted about 10.4 million tons (STCDE) of methane (CH_4) and landfills emitted about 5.5 million tons (STCDE). Together, these two sources accounted for more than 95 percent of Missouri's CH_4 emissions.

[1] Throughout this chapter, the unit of measure is short tons carbon dioxide equivalent (STCDE) unless otherwise specified. As explained in Chapter 1, this unit of measure functions to permit comparisons between different greenhouse gases. For example, 1 million tons STCDE of methane, released into the atmosphere, is expected to have an effect on average temperature equivalent to the effect of releasing 1 million tons of CO_2.

Part 3 estimates trends and projections for nitrous oxide (N_2O) emissions. Agriculture is the leading source of N_2O emissions, just as it is the leading source of methane emissions. The *1990 Inventory* found that in the baseline year use of nitrogenous fertilizers accounted for more than 60 percent of Missouri's CH_4 emissions. Most of the remaining N_2O emissions originate in the transportation sector or with industrial manufacture of nitric acid.

Finally, Part 4 estimates trends and projections for emissions of perfluorinated carbons (PFCs), for which aluminum production is the sole source. Operations at Missouri's sole aluminum plant were the source of about 4.6 million tons (STCDE) of PFCs in 1990. Improvements in processes at the plant resulted in a decrease in PFC emissions of nearly 4 million tons (STCDE) between 1990 and 1996. Table 1 summarizes trends in emissions covered by this chapter. Table 2 summarizes projections of these emissions through 2015.

Table 1 - Estimated trend of GHG emissions from Missouri sources other than fossil fuel combustion, 1990-96

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

	1990	1991	1992	1993	1994	1995	1996
CO_2 emissions excluding energy	11,656	10,998	11,349	10,983	11,504	11,326	11,872
Oxidation of carbon monoxide	1,460	1,433	1,481	1,516	1,570	1,595	1,650
Transportation	1,293	1,279	1,325	1,349	1,396	1,424	1,477
Industrial sector	168	153	156	167	173	171	173
Non-energy uses of fossil fuels	1,345	849	951	910	960	946	982
Industrial sector uses	1,111	640	737	693	733	720	754
Transportation use of lubricants	234	210	214	218	227	226	228
Limestone use	4,445	4,309	4,510	4,150	4,568	4,379	4,834
Cement Production	2,260	2,156	2,382	2,255	2,629	2,424	2,562
Lime Manufacture	1,599	1,597	1,579	1,374	1,413	1,413	1,731
Decomposition of agricultural lime	586	555	549	522	526	541	541
Land use changes	4,407	4,407	4,407	4,407	4,407	4,407	4,407
Net loss of above-ground "sinks"	1,613	1,613	1,613	1,613	1,613	1,613	1,613
Soil carbon release	2,793	2,793	2,793	2,793	2,793	2,793	2,793
Methane emissions	16,712	16,762	17,056	17,569	18,343	18,159	18,290
Agriculture	10,463	10,255	10,410	10,796	11,445	11,140	11,166
Beef cattle operations	5,677	5,634	5,772	5,933	6,288	5,956	6,161
Dairy cattle operations	1,808	1,766	1,701	1,686	1,605	1,552	1,477
Swine operations	2,747	2,623	2,705	2,946	3,321	3,401	3,296
Other livestock operations	170	170	170	170	170	170	170
Rice cultivation	61	61	61	61	61	61	61
Disposal of crop wastes by burning	0	0	0	0	0	0	0
Municipal & industrial waste	5,604	5,851	5,997	6,135	6,261	6,375	6,481
Municipal & industrial landfills	5,501	5,748	5,895	6,032	6,158	6,273	6,378
Municipal waste water treatment	103	103	103	103	103	103	103
Fossil fuel production & distribution	501	513	506	495	494	501	501
Natural gas leakage	496	507	500	490	488	495	495
Coal mining	6	6	6	6	6	6	6
Oil production	0	0	0	0	0	0	0
Highway transportation	143	143	143	143	143	143	143
Nitrous oxide emissions	3,805	3,859	3,925	4,001	3,877	3,855	3,820
Agriculture	2,333	2,388	2,454	2,530	2,406	2,383	2,348
Use of nitrogenous fertilizers	2,333	2,388	2,454	2,530	2,406	2,383	2,348
Disposal of crop wastes by burning	0	0	0	0	0	0	0
Highway transportation	1,080	1,080	1,080	1,080	1,080	1,080	1,080
Nitric acid production	391	391	391	391	391	391	391
PFCs from aluminum production	4,611	1,431	1,090	1,157	1,049	1,065	641
CF_4 emissions*	3,847	1,194	910	965	875	889	535
C_2F_6 emissions*	763	237	181	192	174	176	106
See Part 4.							
All sources except fossil fuel combustion	***5,317***	***5,318***	***5,319***	***5,320***	***5,321***	***5,322***	***5,323***

Table 2 - Estimated GHG emissions from Missouri sources other than fossil fuel combustion, 1990-2015

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

Gross non-energy sources *(excluding forests)*	36,784	33,050	33,420	33,710	34,773	34,405	34,623
	1990	**1996**	**2000**	**2005**	**2010**	**2015**	**Change**
CO_2 emissions excluding energy	11,656	11,872	12,169	12,595	12,984	13,357	1,701
Oxidation of carbon monoxide	1,460	1,650	1,733	1,810	1,857	1,877	417
Transportation	1,293	1,477	1,549	1,616	1,653	1,662	369
Industrial sector	168	173	184	194	204	215	48
Non-energy uses of fossil fuels	1,345	982	1,036	1,074	1,120	1,171	(173)
Industrial sector uses	1,111	754	803	835	875	920	(191)
Transportation use of lubricants	234	228	233	239	245	251	17
Limestone use	4,445	4,834	4,994	5,304	5,600	5,902	1,458
Cement Production	2,260	2,562	2,804	3,106	3,408	3,710	1,450
Lime Manufacture	1,599	1,731	1,731	1,731	1,731	1,731	132
Decomposition of agricultural lime	586	541	459	468	462	462	(124)
Land use changes	4,407	4,407	4,407	4,407	4,407	4,407	0
Net loss of above-ground "sinks"	1,613	1,613	1,613	1,613	1,613	1,613	0
Soil carbon release	2,793	2,793	2,793	2,793	2,793	2,793	0
Methane emissions	16,712	18,290	16,472	17,185	16,861	16,557	(155)
Agriculture	10,463	11,166	10,796	11,234	11,068	11,023	560
Beef cattle operations	5,677	6,161	5,636	6,074	6,210	6,420	744
Dairy cattle operations	1,808	1,477	1,238	1,023	852	700	(1,108)
Swine operations	2,747	3,296	3,691	3,906	3,776	3,672	925
Other livestock operations	170	170	170	170	170	170	0
Rice cultivation	61	61	61	61	61	61	0
Disposal of crop wastes by burning	0	0	0	0	0	0	0
Municipal & industrial waste	5,604	6,481	5,033	5,307	5,149	4,890	(714)
Municipal & industrial landfills	5,501	6,378	4,930	5,205	5,046	4,788	(714)
Municipal waste-water treatment	103	103	103	103	103	103	0
Fossil fuel production & distribution	501	501	501	501	501	501	(1)
Natural gas leakage	496	495	495	495	495	495	(1)
Coal mining	6	6	6	6	6	6	0
Oil production	0	0	0	0	0	0	0
Highway transportation	143	143	143	143	143	143	0
Nitrous oxide emissions	3,805	3,820	3,875	3,872	3,870	3,868	63
Agriculture	2,333	2,348	2,403	2,401	2,399	2,397	63
Use of nitrogenous fertilizers	2,333	2,348	2,403	2,401	2,399	2,397	63
Disposal of crop wastes by burning	0	0	0	0	0	0	0
Highway transportation	1,080	1,080	1,080	1,080	1,080	1,080	0
Nitric acid production	391	391	391	391	391	391	0
PFCs from aluminum production	4,611	641	650	458	437	416	(4,194)
CF_4 emissions*	3,847	535	542	382	365	347	(3,500)
C_2F_6 emissions*	763	106	108	76	72	69	(694)

***See Part 4.**

Greenhouse gas emissions from the sources covered by this chapter are projected to decline by about 2.5 million tons (STCDE), an average annual rate of decline of 0.3 percent. However, this overall statistic masks the different roles played by different sources over time.

Emissions from three sources are projected to decrease by a total of about 6 million tons (STCDE); PFC emissions (4.2 million tons), methane emissions from dairy operations (1.1 million tons) and methane emissions from landfills (0.7 million tons). However, the decrease in PFC emissions occurred early in this period, whereas the decrease in landfill emissions is projected to occur after the year 2000.

Emissions from three other sources are expected to increase by a total of 1.1 million tons (STCDE); primarily methane emissions from beef and swine operations (1.7 million tons) and CO_2 emissions from cement and lime manufacture (1.4 million tons). Emissions from all other sources covered in this chapter are projected to increase by about 0.4 million tons.

These overall statistics mask the very different roles that methane sources played in 1990 through 1996 and that they are projected to play in 1996 through 2015. During 1990 through 1996, when the decrease in overall emissions was driven by PFC emissions, increases in methane emissions offset a portion of this decrease. During this period, methane from landfills increased by about 0.9 million tons (STCDE) and methane from swine and beef operations increased by about 1 million tons (STCDE). Methane from dairy operations decreased by about 0.3 million tons (STCDE).

During 1996 through 2015, decreases in methane sources are projected to drive the decrease in overall emissions. Methane emissions from landfills are projected to decrease by 1.6 million tons (STCDE). Methane emissions from livestock operations are also projected to decrease, with a 0.6 million ton increase in methane emissions from swine and beef operations being offset by a 0.8 million ton decrease from dairy operations. These decreases are expected to occur due to an increase in the flaring and capture of landfill methane, a slowdown in the growth of swine operations in Missouri and continued decline of the state's dairy industry.

Table 3 summarizes the average annual rate of growth for sources of greenhouse gas covered in this chapter.

Table 3 - Annual average rate of growth for sources other than fossil fuel combustion, 1990-1996, 1996-2015 and 1990-2015

	1990-1996	1990-2015	1996-2015
CO_2 emissions excluding energy	0.3%	0.5%	0.6%
Oxidation of carbon monoxide	2.1%	1.0%	0.7%
Transportation	2.3%	1.0%	0.6%
Industrial sector	0.5%	1.0%	1.2%
Non-energy uses of fossil fuels	-5.1%	-0.6%	0.9%
Industrial sector uses	-6.2%	-0.8%	1.1%
Transportation use of lubricants	-0.5%	0.3%	0.5%
Limestone use	1.4%	1.1%	1.1%
Cement Production	2.1%	2.0%	2.0%
Lime Manufacture	1.3%	0.3%	0.0%
Decomposition of agricultural lime	-1.3%	-0.9%	-0.8%
Methane emissions	1.5%	0.0%	-0.5%
Agriculture	1.1%	0.2%	-0.1%
Beef cattle operations	1.4%	0.5%	0.2%
Dairy cattle operations	-3.3%	-3.7%	-3.9%
Swine operations	3.1%	1.2%	0.6%
Municipal & industrial waste	2.5%	-0.5%	-0.3%
Municipal & industrial landfills	2.5%	-0.6%	-0.3%
Nitrous oxide emissions	0.1%	0.1%	0.1%
Agriculture	0.1%	0.1%	0.1%
Use of nitrogenous fertilizers	0.1%	0.1%	0.1%
PFCs from aluminum production	-28.0%	-9.2%	-2.2%
CF_4 emissions*	-28.0%	-9.2%	-2.2%
C_2F_6 emissions*	-28.0%	-9.2%	-2.2%

See Part 4.

Part 1: CO_2 emissions from sources other than fossil fuel combustion — trends and projections

Although fossil fuel combustion is the most important source of CO_2 emissions in Missouri, the *1990 Inventory* identified several additional sources of CO_2 emissions in the state. CO_2 emissions from these additional sources are projected to increase at a modest 0.5 percent annual growth rate from 1990 to 2015.

Through 2015, CO_2 emissions from Missouri cement manufacture are projected to increase by about 1.5 million tons per year. Otherwise, the projected changes in emissions from these sources are minor when compared to the magnitude of projected increases from energy use.

Section 1 presents trends and projections for oxidation of carbon monoxide (CO). CO is emitted as a byproduct of energy use in industry and transportation. Although CO is not a greenhouse gas, it oxidizes into CO_2 within a year.

Section 2 presents trends and projections for non-energy uses of fossil fuels. Petroleum and natural gas are used in some manufacturing processes that do not involve combustion but still lead to CO_2 emissions. The CO_2 emissions typically are lower than would have occurred if the fossil fuel were burned, since some carbon remains sequestered in the product.

Section 3 presents trends and projections for CO_2 emissions that result from a variety of agricultural and industrial uses of limestone, including cement manufacture.

A final source of CO_2 emissions is changes in land use. Some land use changes, such as conversion of forest land to other uses, reduce the ability of land to sequester carbon and are therefore sources of net CO_2 emissions. Other land use changes, such as permitting an agricultural field to revert to forest, may increase sequestration.

Chapter 7 of the *1990 Inventory* estimated changes in above-ground and below-ground carbon from land use changes using data gathered by the Natural Resource Conservation Service during its 1980 and 1990 Missouri Natural Resource Inventory surveys. Because no subsequent inventory has occurred, no data is available to revise the estimates presented in the *1990 Inventory*. Therefore, in estimating the 1990 to 1996 trends and the 1990 to 2015 projections, this study assumes that CO_2 emissions from land use changes estimated for 1990 will continue annually through 2015.

Section 1: CO_2 emissions from oxidation of carbon monoxide

Chapter 2 of the *1990 Inventory* sets out the methodology and rationale for including oxidation of carbon monoxide in the transportation and industrial sectors as a source of CO_2. The resulting trends and projections, summarized in Tables 4 and 5, assume that carbon monoxide emissions in the transportation sector will increase at the same rate as projected gasoline and diesel use in that sector, and that industrial CO_2 emissions from this source will increase at the same rate as industrial primary fossil fuel use.

The resulting trend and projection estimates are as follows.

Table 4 - Trends in estimated CO_2 emissions from oxidation of CO in Missouri, 1990-96

Units: 1,000 Short Tons Carbon Dioxide (CO_2)

	1990	1991	1992	1993	1994	1995	1996
Oxidation of carbon monoxide	1,460	1,433	1,481	1,516	1,570	1,595	1,650
Transportation	1,293	1,279	1,325	1,349	1,396	1,424	1,477
Industrial	168	153	156	167	173	171	173

Table 5 - Projections of estimated CO_2 emissions from oxidation of CO in Missouri, 1990-96

Units: 1,000 Short Tons Carbon Dioxide (CO_2)

	1990	1996	2000	2005	2010	2015
Oxidation of carbon monoxide	1,460	1,650	1,733	1,810	1,857	1,877
Transportation	1,293	1,477	1,549	1,616	1,653	1,662
Industrial sector	168	173	184	194	204	215

As described in Chapter 4, the estimated growth rates for primary fossil fuel consumption in the transportation and industry sectors depend on the estimation method. The projections shown in Table 5 are based on the AEO method for projecting transportation and industry fossil fuel combustion.

As Table 6 indicates, the projection of carbon monoxide from the transportation sector would increase if it were based on the SS and CT methods for projecting energy use because these methods project faster transportation energy growth than the *Annual Energy Outlook 1997*. The Energy Information Administration, which produces the *Annual Energy Outlook*, has also revised its gasoline use projections upward from those that appear in the *Annual Energy Outlook 1997*. On the other hand, the projection for the industrial sector is larger than it would be using the CT projection method.

Table 6 - Comparison of CT, SS and AEO projections of Missouri GHG emissions from oxidation of CO in 2015

Units: 1,000 Short Tons Carbon Dioxide (CO_2)

	CT	SS	AE
Oxidation of Carbon Monoxide	2,039	1,982	1,877
Transportation	1,913	1,732	1,662
Industrial	126	250	215

Section 2: CO_2 emissions from non-energy uses of fossil fuels

In Missouri, lubricants and a portion of natural gas, LPG and "other petroleum products"[2] are used for non-energy purposes in the transportation and industrial sectors. Table 7 summarizes the *1990 Inventory* estimates for the portion of each fuel going to non-energy uses in 1990. To expedite the process of estimating non-energy related emissions from these sources between 1991 and 2015, the study assumes the proportion of each fuel used for non-energy purposes remains constant at the 1990 level through 2015.

Combustion of fossil fuels for energy leads to the oxidation of nearly all the carbon in the fuel. In non-energy uses of fossil fuels, however, a large portion of the carbon is frequently sequestered rather than oxidized. This study takes from the *1990 Inventory* the following estimates of the percentage of carbon sequestration in non-energy uses of fossil fuels:

- 50 percent of transportation lubricants;
- 50 percent of industrial lubricants, natural gas and petroleum coke; and
- 80 percent of industrial LPG, naptha (> 104F) and other oils (<104F).

A CO_2 emissions multiplier for non-energy use was determined for each of these fuels based on the estimated carbon content and level of sequestration for each fuel. Table 7 summarizes these multipliers.

Table 7 - Parameters for estimating CO_2 emissions from non-energy uses of fossil fuels

	Non-Energy Use as Percentage of Total Use		CO_2 Emissions
	Transportation	**Industrial**	**Multiplier**
Lubricants	100%	100%	80.9
Natural gas	N/A	4.1%	2.4
LPG	N/A	1.7%	0.5
Other petroleum	N/A	67%	31.9

When the coefficients in Table 7 are applied to consumption estimates and projections for the fossil resources listed in Table 7 for 1991-2015, the resulting estimates of CO_2 emissions from non-energy use are as follows:

[2] These fuels are defined in Appendix A of the USDOE/EIA *State Energy Data Report*, which adopts the standard reporting categories of its federal and industry data sources. The fossil fuels included as “other petroleum products” include naptha (>104˚F), other oils (<104˚F), pentanes plus, special naptha, waxes, petroleum coke and “miscellaneous petroleum products.”

Table 8 - Trends in estimated CO_2 emissions from non-energy uses of fossil fuels

Units: 1,000 Short Tons Carbon Dioxide (CO_2)

	1990	1991	1992	1993	1994	1995	1996
Industry							
Lubricants	168.53	150.77	153.72	156.52	163.60	162.76	163.67
Natural gas	65.74	68.79	69.85	73.00	85.90	82.57	83.77
LPG	1.54	1.73	1.58	2.19	2.17	2.10	2.37
Other petr.	874.73	418.56	511.99	461.01	481.07	472.17	504.37
Subtotal	1,110.55	639.85	737.13	692.73	732.74	719.60	754.17
Transportation	234.32	209.63	213.73	217.63	227.46	226.30	227.56
Total	***1,344.88***	***849.48***	***950.86***	***910.36***	***960.20***	***945.90***	***981.73***

Table 9 - Projections of CO_2 emissions from non-energy uses of fossil fuels in 2005

Units: 1,000 Short Tons Carbon Dioxide (CO_2)

	1990	1995	2000	2005	2010	2015
Industry						
Lubricants	168.53	162.76	167.28	171.79	176.30	180.82
Natural gas	65.74	82.57	93.33	98.77	104.74	108.76
LPG	1.54	2.10	2.23	2.55	2.87	3.31
Other petr.	874.73	472.17	540.18	562.24	591.12	627.11
Subtotal	1,110.55	719.60	803.01	835.36	875.04	919.99
Transportation	234.32	226.30	232.58	238.85	245.13	251.40
Total	***1,344.88***	***945.90***	***1,035.59***	***1,074.21***	***1,120.17***	***1,171.39***

As explained in Chapter 2, the 1990 and 1991 decline in "other petroleum" reported in these tables is partly an artifact of a change in USDOE/EIA reporting procedures.

Section 3: CO_2 emissions from agricultural and industrial uses of limestone

Agricultural and industrial uses of limestone were included as a source of CO_2 emissions in the *1990 Inventory*. The methodology and rationale for inclusion are summarized in the Methodological Appendix to Chapter 5.

Agricultural lime is applied with the intention that it will decompose into calcium and various byproducts including CO_2. By Missouri law, agricultural lime must be at least 65 percent calcium carbonate ($CaCO_3$).

The rate of decomposition of agricultural lime varies depending on its mesh (size) and other factors. Use of a 10-year average for application of agricultural lime is sufficient to remove rate of decomposition as an issue in estimating emissions. For example, in order to estimate CO_2 emissions in 1990, data for the years 1981 to 1990 is used to determine the average rate of application over the previous 10 years.

Missouri agricultural lime usage data between 1981 and 1997[3] was obtained from Fertilizer Control Services (FCS), Agricultural Experiment Station, University of Missouri-Columbia. It was assumed that Missouri farmers would continue to apply agricultural lime during 1998 through 2015 at the rate of 1,614,673 tons per year, the average rate of application between 1990 and 1997 calculated from the FCS data. The FCS usage data was used to estimate the 10-year averages for 1990 to 1996 in Table 10. Similarly, 10-year averages were calculated for all subsequent years. Lower-bound estimates of $CaCO_3$ for 1990 to 1996 are shown in Table 10; lower-bound estimates for future years are shown in Table 11. These are estimated by multiplying 10-year average use estimates by 65 percent. The resulting CO_2 emissions are estimated by multiplying estimated $CaCO_3$ by 44/100, the ratio of the molecular weight of CO_2 to $CaCO_3$.

Table 10 - Trend of estimated CO_2 emissions from agricultural lime use in Missouri, 1990-96

Units: Tons Carbon Dioxide (CO_2)

	1990	1991	1992	1993	1994	1995	1996
FCS agric. lime data	1,708,651	1,482,467	1,631,184	1,083,952	1,648,914	1,927,803	1,804,151
Ten-year average	2,048,967	1,940,704	1,918,412	1,824,067	1,839,440	1,892,758	1,911,824
Lower bound $CaCO_3$	1,331,829	1,261,457	1,246,968	1,185,644	1,195,636	1,230,293	1,242,686
Lower bound CO_2	586,005	555,041	548,666	521,683	526,080	541,329	546,782

[3] Estimates for 1997 were received while the draft report was undergoing final review and were incorporated into the emissions estimates shown here.

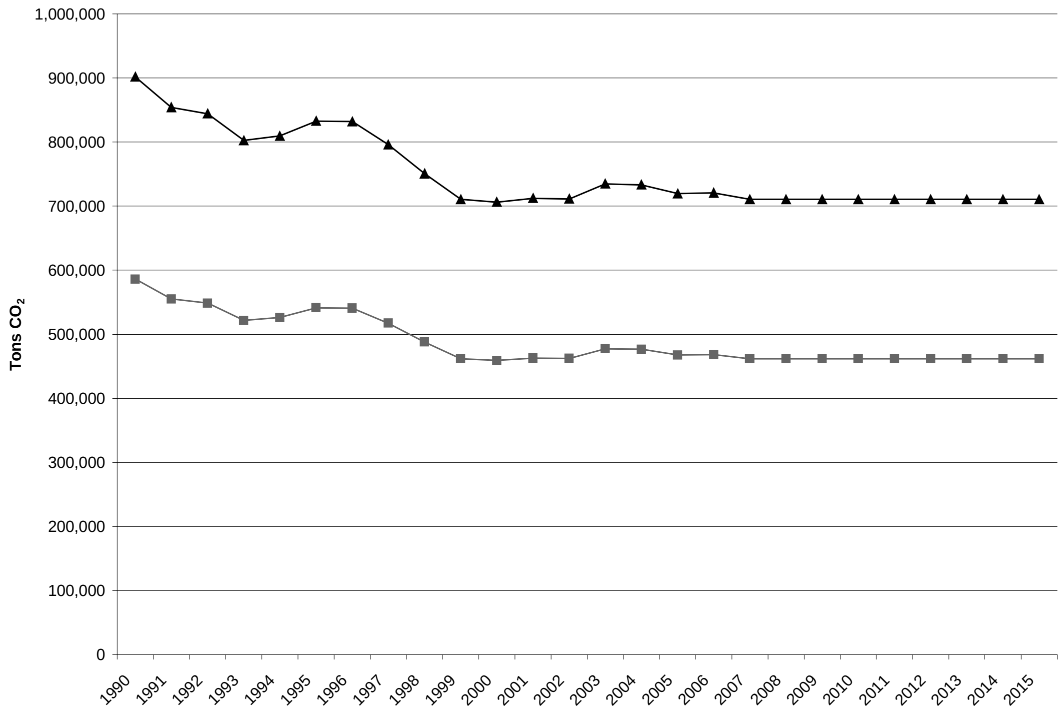
Table 11 - Projections of estimated CO_2 emissions from agricultural lime use in Missouri, 1990-2015

Units: Tons Carbon Dioxide (CO_2)

	1990	2000	2005	2010	2015
Lower bound $CaCO_3$	1,331,829	1,043,429	1,062,867	1,049,538	1,049,538
Lower bound CO_2	586,005	459,109	467,661	461,797	461,797

As Chart 1 indicates, use of the lower bound of CO_2 emissions from agricultural lime use provides a conservative estimate of CO_2 emissions from this source. The upper bound illustrated in Chart 1 represents estimated emissions if 100 percent of the agricultural lime applied consists of calcium carbonate. The actual calcium carbonate content of most agricultural lime applied in Missouri is probably greater than 65 percent. However, the lower bound of 65 percent is used for trends and projections estimates in this report to compensate for the possibility that some calcium carbonate is leached or enters chemical pathways that do not result in CO_2 emissions.

Chart 1 - Upper and lower bounds of estimated CO_2 emissions from agricultural lime use in Missouri, 1990-2015



Industrial uses of limestone include cement manufacture and lime manufacture, uses which lead to the chemical decomposition of calcium carbonate and the release of CO_2.

The primary release of CO_2 during cement production occurs in the manufacture of clinker. About 97 percent of the cement manufactured in Missouri in 1990 was Portland cement; the remaining 3 percent was masonry cement. Clinker is the only source of CO_2 emissions in the manufacture of Portland cement. The production of masonry cement involves the addition of lime beyond that contained in clinker.

Data on Missouri cement and lime production from 1990 to 1996 were obtained from the Division of Mineral Commodities (DMC) of the U.S. Department of Interior's Bureau of Mines. Production of Portland cement between 1997 and 2015 was projected by linear regression on the 1990 to 1996 data. Missouri clinker production for the years after 1990 was estimated assuming that the ratio of clinker to Portland cement would remain constant at the 1990 ratio.

Table 12 summarizes the DMC data as well as trend estimates, and Table 13 summarizes the corresponding projections through 2015. The analysis assumes that production of masonry cement remains constant after 1990 (approximately 127,000 tons).

Table 12 - Trends in cement and clinker production in Missouri, 1990-96

Units: Tons

	1990	1991	1992	1993	1994	1995	1996
Cement production	4,481,000	4,276,000	4,724,501	4,472,072	5,213,926	4,808,276	5,082,402
Clinker production	4,451,000	4,247,372	4,692,871	4,442,132	5,179,019	4,776,085	5,048,376
Masonry cement	127,000	127,000	127,000	127,000	127,000	127,000	127,000
Lime production	2,037,000	2,035,000	2,012,000	1,750,000	1,800,000	1,800,000	2,204,620

Table 13 - Projected cement and clinker production in Missouri through 2015

Units: Tons

	1990	2000	2005	2010	2015
Cement production	4,481,000	5,562,143	6,161,818	6,761,494	7,361,169
Clinker production	4,451,000	5,524,904	6,120,565	6,716,226	7,311,887
Masonry cement	127,000	127,000	127,000	127,000	127,000

The estimation methodology for industrial emissions uses the following emissions coefficients to estimate CO_2 emissions per ton of clinker, masonry cement or lime produced:

Table 14 - Emissions coefficients per ton of clinker, masonry cement or lime

	Tons CO_2 per ton production
Clinker production	0.507
Masonry cement	0.0224
Lime production	0.785

Use of these coefficients results in the trend estimates summarized in Table 15 and projection estimates summarized in Table 16. The projected growth in CO_2 emissions is due primarily to an expected increase in cement production.

Table 15 - Estimated CO_2 emissions from industrial and agricultural use of limestone, 1990-96

Units: Tons Carbon Dioxide (CO_2)

	1990	1991	1992	1993	1994	1995	1996
Clinker production	2,256,657	2,153,418	2,379,285	2,252,161	2,625,763	2,421,475	2,559,526
Masonry cement	2,845	2,845	2,845	2,845	2,845	2,845	2,845
Lime production	1,599,045	1,597,475	1,579,420	1,373,750	1,413,000	1,413,000	1,730,627
Agricultural lime	586,005	555,041	548,666	521,683	526,080	541,329	540,679

Table 16 - Projected CO_2 emissions from industrial and agricultural use of limestone through 2015

Units: Tons Carbon Dioxide (CO_2)

	1990	2000	2005	2010	2015
Clinker production	2,256,657	2,801,127	3,103,127	3,405,127	3,707,127
Masonry cement	2,845	2,845	2,845	2,845	2,845
Lime production	1,599,045	1,730,627	1,730,627	1,730,627	1,730,627
Agricultural lime	586,005	459,109	467,661	461,797	461,797
Total	4,444,551	4,993,707	5,304,259	5,600,395	5,902,395
Growth rate		***1.2%***	***1.2%***	***1.2%***	***1.1%***

Part 2: Methane emissions — trends and projections

The *1990 Inventory* identified two major sources of anthropogenic methane emissions in Missouri — agricultural sources, particularly methane emissions from livestock and waste disposal in municipal and industrial landfills, together accounting for more than 95 percent of methane emissions. The only other significant source was leakage from natural gas pipelines, which contributed an estimated 3 percent of methane emissions in 1990. The remaining 1 percent of anthropogenic methane emissions originated from transportation, oil production and coal mining.

This study estimates trends in the agricultural and landfill sources of methane emissions between 1990 and 1996 and projects emissions from these sources between 1996 and 2015. It assumes that methane emissions from other sources have remained constant since 1990.

Table 17 summarizes trend estimates for Missouri methane emissions between 1990 and 1996, and Table 18 summarizes projections through 2015. In all cases, STCDE estimates were derived by applying the Global Warming Factor (GWF) of 24.5 STCDE per ton of CH_4.

Table 17 - Estimated methane emissions in Missouri, 1990-96

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

	1990	1991	1992	1993	1994	1995	1996
Agriculture	10,463	10,255	10,410	10,796	11,445	11,140	11,166
Beef cattle	5,677	5,634	5,772	5,933	6,288	5,956	6,161
Dairy cattle	1,808	1,766	1,701	1,686	1,605	1,552	1,477
Swine	2,747	2,623	2,705	2,946	3,321	3,401	3,296
Other livestock	170	170	170	170	170	170	170
Rice cultivation	61	61	61	61	61	61	61
Burning crop wastes	0	0	0	0	0	0	0
Municipal waste	5,419	5,633	5,738	5,836	5,922	5,999	6,066
Municipal & industrial landfills	5,316	5,530	5,636	5,733	5,820	5,896	5,964
Municipal waste water treatment	103	103	103	103	103	103	103
Fossil fuel prod'n & dist'n	501	513	506	495	494	501	501
Natural gas leakage	496	507	500	490	488	495	495
Coal mining	6	6	6	6	6	6	6
Oil production	0	0	0	0	0	0	0
Highway transportation	143	143	143	143	143	143	143
Total	***16,527***	***16,544***	***16,797***	***17,270***	***18,005***	***17,783***	***17,876***

Table 18 - Projected methane emissions in Missouri, 1990-2015

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

	1990	1996	2000	2005	2010	2015
Agriculture	10,463	11,166	10,796	11,234	11,068	11,023
Beef cattle	5,677	6,161	5,636	6,074	6,210	6,420
Dairy cattle	1,808	1,477	1,238	1,023	852	700
Swine	2,747	3,296	3,691	3,906	3,776	3,672
Other livestock	170	170	170	170	170	170
Rice cultivation	61	61	61	61	61	61
Burning crop wastes	0	0	0	0	0	0
Municipal waste	5,604	6,481	5,033	5,307	5,149	4,890
Municipal & industrial landfills	5,501	6,378	4,930	5,205	5,046	4,788
Municipal waste water treatment	103	103	103	103	103	103
Fossil fuel prod'n & dist'n	501	501	501	501	501	501
Natural gas leakage	496	495	495	495	495	495
Coal mining	6	6	6	6	6	6
Oil production	0	0	0	0	0	0
Highway transportation	143	143	143	143	143	143
Total	***16,712***	***18,290***	***16,472***	***17,185***	***16,861***	***16,557***

Section 1: Methane emissions from municipal and industrial landfills

Landfills are the most concentrated source of anthropogenic methane emissions in Missouri. More methane is emitted from livestock operations than landfills, but most of these operations are relatively small and spread widely across the state. This study estimates that in 1990, Missouri's sanitary and industrial landfills produced about 263,000 tons (STCDE) of methane;[4] by comparison, livestock operations produced about 426,000 tons (STCDE) of methane.

Methane production from Missouri landfills has increased every year since 1990. The increase is projected to continue until methane production peaks in the year 2006. The projected increase is based on the assumption that waste, once placed in a landfill, continues to generate methane for about 30 years. As documented in the *1990 Inventory*, large sanitary landfills are a relatively recent phenomenon in Missouri. Since nearly all the waste in Missouri's landfills has been placed there since 1976, it follows that this waste will continue to generate methane through at least 2006 and that annual additions of new waste will lead to an increase in annual emissions.

After about 2006, annual methane production from Missouri's landfills is projected to decrease. This reflects reductions in annual landfill waste receipts that have occurred after 1991 following passage of legislation in 1990 that set waste reduction goals, as well as the transition of waste that is over 30 years old from a methanogenically active stage to a "stabilized" stage in which emissions have ceased.

This study projects that Missouri landfills will produce about 347,000 tons (STCDE) of methane in the year 2006 and 324,000 tons (STCDE) in the year 2015. These are midpoint estimates. The corresponding range estimates are 277,000 to 417,000 tons (STCDE) in 2006 and 256,000 to 391,000 tons (STCDE) in 2015. The wide range of these estimates reflect uncertainty about the projected waste-in-place in landfills as well as uncertainties related to the estimation model itself.

Regardless of the accuracy of these projections, it is likely that methane production will increase until the year 2006 and then decrease through 2015. However, this pattern could be affected by waste exports. Missouri's two largest metropolitan areas are located at state borders with Kansas and Illinois, and a significant portion of the waste generated in these metropolitan areas crosses state lines. In recent years, Missouri has exported approximately one-third of its solid waste. A decrease in the net flow of waste from Missouri to bordering states could result in an increase in landfill receipts and methane generation even if the per capita rate of waste is decreasing and the rate of recovery or recycling is increasing in Missouri. Similarly, an increase in waste export could reduce receipts and methane generation in Missouri landfills. Since future waste export rates are dependent on many local factors and inherently difficult to project, this study assumes that exports will continue at the present level.

[4] This is the average of the estimated range for gross potential landfills methane emissions in 1990, 183,000 to 343,000 tons (STCDE). The corresponding range estimate for 2006 is 277,000 to 417,000 tons (STCDE), and for 2015 is 256,000 to 391,000 tons (STCDE).

Net methane emissions from Missouri landfills are lower than the *production* of methane because some methane produced by landfills is oxidized before reaching the surface, and some that reaches the surface is flared or recovered instead of entering the atmosphere. For example, if all the methane produced by Missouri landfills in 1990 had entered the atmosphere, emissions equal to about 6.4 million tons (STCDE) would have occurred. Because some methane was oxidized, flared or captured, only about 5.5 million tons (STCDE) of methane entered the atmosphere.

Although methane production is projected to peak in 2006, net methane emissions are projected to peak in 1999. The projected decrease in net emissions is due to an increase in methane flaring and capture that is expected to occur as a result of federal and state regulations that require some Missouri landfills to develop landfill gas collection systems by the year 2000.[5]

This study projects that net methane emissions will equal about 6.7 million tons (STCDE) in 1999, 4.9 million tons (STCDE) in 2000, 5.2 million tons (STCDE) in 2006 and 4.8 million tons (STCDE) in 2015. At no point between 2000 and 2015 are net emissions expected to reach their 1990 level.

Regardless of the accuracy of these projections, it is likely that net methane emissions will peak in the year 1999, decrease to below 1990 levels in the year 2000, gradually increase again until 2006, and then decrease through 2015. However, this pattern could be affected by landfill operator decisions in response to federal regulations or opportunities to invest in methane capture. For example, net emissions could be higher if landfill operators delay their compliance with federal and state regulations, or lower than projected if landfill operators decide to invest in methane capture beyond the requirements of these regulations. Since these decisions are inherently unpredictable, it is assumed that operators will meet but not exceed federal and state requirements.

This study's estimates of landfill methane emissions, like estimates in the *1990 Inventory*, are calculated using a statistical estimation model prescribed by the U.S. Environmental Protection Agency (USEPA) in its *States Workbook*. The model provides equations to estimate the *potential gross emissions* from large and small municipal landfills based on estimated waste-in-place (WIP) in these landfills. Potential gross emissions from industrial landfills are estimated based on the municipal landfill estimates. Finally, the estimates of potential gross emissions are discounted to account for oxidation, flaring and capture.

[5] *Federal Register*, Vol. 61, No. 49, p. 9905, March 12, 1996. The Missouri Air Pollution Control Program is publishing regulations for St. Louis and the remainder of the state that affect some landfills not covered by the federal regulation. The regulations are intended to control non-methane organic compounds (NMOCs) but the systems to collect and dispose of NMOCs are expected to remove methane as well; USEPA, *Greenhouse Gas Emissions from Municipal Waste Management, Draft Working Paper*, March 1997, Chapter 7.

The USEPA's statistical model is based on USEPA research completed by the Air and Energy Engineering Research Laboratory (AAERL) in 1991 and the Office of Air and Radiation (OAR) in 1993. The purpose of the AAERL study[6] was to determine whether a simple statistical model based on physical characteristics of landfills could be used to estimate methane emissions from landfills at an aggregate (global or national) level. Using data from a sample of 21 landfills, the AAERL study tested the statistical relationship between methane emissions and a number of variables assumed to affect emissions from landfills.[7] Although a number of factors were correlated with emissions, the study concluded that waste-in-place explained the largest portion of the observed variation in emissions and that a simple model relating emissions to total amount of waste-in-place is adequate for estimating methane production.

Drawing on the AAERL study, the OAR study[8] used linear regression to estimate the relationship between methane emissions and waste-in-place in large U.S. landfills. To estimate the relationship, the study used data for 85 U.S. landfills with over 1.1 million tons of waste-in-place, drawn from a database of landfills with methane collection systems. From discussions with industry experts, the analysts concluded that these 85 landfills are representative of large landfills generally. Although the analysts understood that many factors can influence landfill emissions, they argued that "since [these 85 landfills] vary in depth, age, regional distribution and other factors … a simple model based [on data for these landfills] should provide a robust estimate of methane emissions from landfills."

The OAR study developed a second equation to estimate emissions from small landfills based on the average methane generation rate for the 85 large landfills in the database. The study used the large landfill data rather than small landfill data in the database because the small landfills included in the database were "gassier" than average. The study acknowledged that this method implicitly assumes that "with the exception of size, the relevant characteristics of small landfills are similar to the characteristics of the larger landfills in the data set."

This background is necessary in order to understand that there are several sources of uncertainty and possible error in this study's emissions estimates. Some derive from assumptions made by the AAERL/OAR model. Others are associated with the task of estimating or projecting the waste-in-place data that is required by the model.

1. The simplicity of the AAERL/OAR model raises the issue whether it is properly specified. As acknowledged in both the AAERL and OAR studies, many factors related to climate, characteristics of the waste and characteristics of the design and operation of a landfill may affect methane generation. However, it must be recognized that the intended use of the model is to estimate emissions at an aggregate (national or global) level. For tasks such as assessing the feasibility of capturing methane at an individual site, USEPA recommends that other models be used.[9]

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[6] Peer, Rebecca L., et. al., *Development of an Empirical Model of Methane Emissions from Landfills,* EPA-600/R-92-037, March 1992.

[7] Variables tested in addition to waste-in-place included climate; refuse characteristics such as moisture content, composition, age and pH; landfill characteristics such as age, depth, volume and surface area; and waste-handling practices.

[8] USEPA/OAR, *Anthropogenic Methane Emissions in the United States: Estimates for 1990: Report to Congress,*1993.

[9] Personal communication, Susan Thornloe, USEPA, October 1, 1998. One recommended model is LandGEM.

The AAERL study concluded that waste-in-place explains a sufficient portion of the variation in landfill emissions to serve as the basis for a model intended to estimate emissions across an aggregation of landfills. However, the study tested some but not all of the possible factors and its analytic approach was limited to regression methods conducted on a small sample of only 21 landfills. Therefore, until other studies confirm the AAERL study's results, its conclusions should be considered tentative.

2. As explained in the *1990 Inventory*, the waste sites in Missouri include many landfills that are small by USEPA standards (less than 1.1 million tons of waste-in-place) and also many abandoned town dumps whose methane emissions characteristics are largely unknown. As prescribed by the *States Handbook*, this study uses the AAERL/OAR model to estimate emissions from these sources. However, application of the model to these waste sites is a possible source of error because the AAERL/OAR model was estimated using data from the largest landfills in the U.S. The OAR study concedes that the model does not readily apply to abandoned waste dumps and that the basis for estimating emissions from small landfills needs to be improved."[10] This study's estimates are adjusted in two ways to account for this possible source of error. The estimates for emissions from small landfills are assigned a ±20 percent range of error. In addition, as described in the *1990 Inventory*, the estimates of waste-in-place in town dumps are discounted, with a higher discount rate assigned in the low waste-in-place scenario.

3. Aside from issues of landfill size, there are other bases on which to ask whether the landfills used to estimate the model are representative of landfills in Missouri. The model was developed to estimate emissions at a highly aggregated (global or national) level. When it is applied to estimates at a state level, it is possible that certain variables that "average out" at the global or national level may be significant at a state level. For example, landfills in Missouri are probably younger on average than landfills in the sample database, but the model assumes that the rate of emissions is constant over a 30 year period and for all landfills. Generation rates of methane may vary over time and have been determined to be highest at closure. Moreover, Subtitle D landfills, also known as dry tomb landfills, are drier and decompose more slowly than pre-Subtitle D landfills.

Another example of a variable that may be significant at the state level is average temperature. The emissions coefficients in USEPA's model for state methane emissions from livestock waste are adjusted for average state temperature. A similar adjustment might be appropriate in the model for state landfill emissions.

4. The model assumes that waste deposited in a landfill generates methane for 30 years. Thus, methanogenically active waste-in-place for a landfill for any given year is assumed to be the total of waste placed in the landfill during the previous 30 years. The assumed 30-year time horizon could be an overestimate or underestimate.

5. In Missouri, the percentage of organic material in the municipal waste stream has been reduced since 1990 in response to statutory prohibition against inclusion of yard waste and the increasing market value of waste paper. The model is incapable of incorporating this information because its variables do not include waste stream composition.

[10] ibid., p. 4-34.

6. Estimates of landfill waste-in-place are based on estimates of annual landfill receipts of solid waste. DNR's Solid Waste Management Program began collecting fairly reliable data on landfill receipts in 1990, but there is no reliable data on landfill receipts before 1990. Therefore, estimates of current landfill waste-in-place are subject to error. To account for this source of error, this study continues to use the high waste-in-place and low waste-in-place scenarios described in the *1990 Inventory*.

Future landfill receipts are, by their nature, uncertain. This study extends the high waste-in-place and low waste-in-place scenarios to account for this uncertainty. The scenarios make different assumptions about future population growth, per capita waste generation and waste recycling and recovery. However, these scenarios do assume that waste export rates will remain constant; as previously noted, landfill receipts could be affected by changes in waste export rates.

7. A final source of uncertainty is the relationship between methane generation and net emissions. As the OAR study concedes, the 10 percent average oxidation rate prescribed by the *States Workbook* is based on limited observations and may be too high or too low.[11] In addition, the impact of new federal and state regulations that require certain landfills to develop landfill gas collection systems is uncertain. These regulations are expected to result in an increase in the flaring or capture of methane from Missouri landfills, but to estimate the increase it is necessary to make assumptions about how many landfills will install gas collection systems and about the recovery efficiency for the systems that are installed.

The issues listed above are all significant issues that should be taken into account when assessing the estimates presented in this report. Nevertheless, based on USEPA's review of available alternatives, the methodology recommended by USEPA appears to be the best available to estimate statewide landfill emissions.[12] Development of an alternative methodology is beyond the scope of this project, and any methodology would be subject to many of the sources of uncertainty listed above. Moreover, since other states involved in USEPA projects are also using the methodology recommended by USEPA, its use assures the comparability of estimates for Missouri and other states.

The remainder of this section describes the procedure used to estimate and project methane emissions from Missouri landfills. Two steps are described: estimation of methanogenically active waste-in-place and distribution of waste-in-place between small and large landfills; and application of the USEPA methodology to estimate methane production and net methane emissions.

Step 1: Estimation of methanogenically active waste-in-place (WIP) and distribution of WIP between small and large landfills

Use of the AAERL/OAR model requires an estimate of methanogenically active waste-in-place (WIP) in Missouri landfills. As described in the *1990 Inventory*, WIP for any given year is estimated by aggregating landfill receipts for the previous 30 years.

[11] ibid., p. 4-34.

[12] Although this is the most suitable methodology for estimating statewide emissions, better methodologies are available for estimating emissions from individual landfills.

The *1990 Inventory* develops a model for estimating receipts prior to 1991. This model estimates Missouri landfill receipts as the residual of the amount of waste generated minus the amount of waste going to destinations other than Missouri landfills. Because there are multiple sources of uncertainty about waste generation and disposal before 1990, the *1990 Inventory* develops low-WIP and high-WIP scenarios. The high-WIP scenario estimate for 1990 WIP is about 34 million tons greater than the low-WIP estimate. A large portion of this difference is because the low-WIP scenario heavily discounts receipts of pre-1973 waste, which were deposited primarily in town dumps rather than sanitary landfills. Chapter 3, Section 2 of the *1990 Inventory* describes in detail this and other assumptions and methods used to estimate methanogenically active WIP for years prior to 1991.

Since 1991, Missouri landfill operators have been required by law to report tonnage of waste received. Table 19 summarizes estimates of tonnage received at Missouri landfills between 1991 and 1996. These estimates were aggregated from landfill reports to the Missouri Department of Natural Resources' Solid Waste Management Program (SWMP). Reported landfill receipts decreased nearly 12 percent between 1991 and 1992, and continued to decrease at a decelerating rate that approached 3 percent by 1996. The decrease in receipts between 1990 and 1996 reflects a legislatively mandated effort to reduce the quantity of waste entering Missouri landfills as well as expanded recycling due to an increase in the market value of waste products, especially waste paper.

Table 19 - Estimated aggregate receipts of solid waste at Missouri municipal landfills, 1991-96

Units: 1,000 Short Tons

1991	1992	1993	1994	1995	1996
4,896	4,318	4,157	3,957	3,768	3,624

In order to estimate future methane emissions from landfills, it is necessary to estimate future in-state landfill receipts. Projected receipts are subject to many sources of uncertainty. Table 20 summarizes low-WIP and high-WIP projections of Missouri landfill receipts for selected years from 1997 to 2015.

The low-WIP projection is based on the assumption that Missouri landfill receipts will decrease by 3 percent per year until they reach approximately 50 percent of the 1991 level in 2008 and that after 2008, receipts will remain constant at the 2008 level.[13] The high-WIP projection is based on the assumption that after 1997, per capita waste going to Missouri landfills will remain constant, and landfill receipts will grow at the rate of Missouri population increase.

These assumptions were made to reflect the likely range of variation in factors such as population growth, waste generation rates, recovery and recycling. However, these assumptions do not attempt to anticipate possible changes in patterns of waste export and import. Thus, future receipts could range higher or lower than the projections in Table 20 if there are major changes in the amount of waste moving between Missouri and neighboring states.

[13] Personal communication, Kathy Weinsaft, Missouri SWMP, June 16, 1997.

Table 20 - Projected receipts of solid waste at Missouri municipal landfills, by scenario, 1997-2015

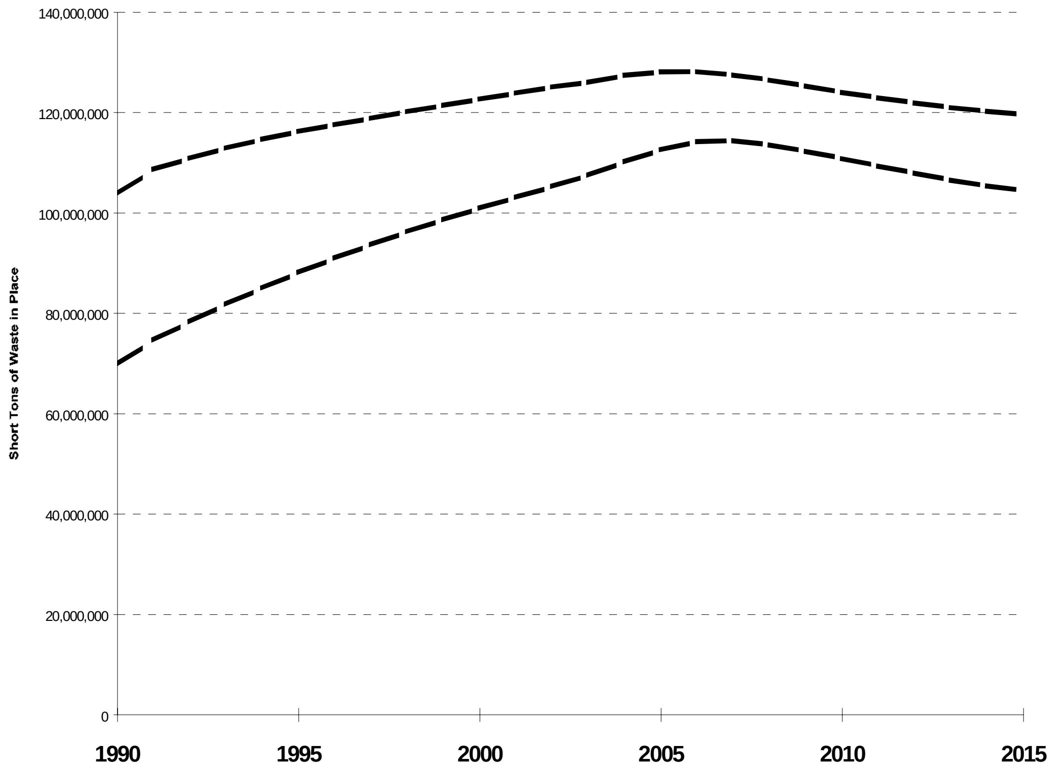
Units: 1,000 Short Tons

	1997	1998	1999	2000	2005	2008	2010	2015
Low WIP	3,515	3,410	3,308	3,208	2,928	2,928	2,928	2,928
High WIP	3,638	3,653	3,667	3,681	3,752	3,796	3,826	3,901

The estimate of aggregate WIP for any given year is estimated as the sum of methanogenically active[14] landfill receipts for the past 30 years. As Chart 2 indicates, the resulting projections indicate that WIP in Missouri's landfills will continue to increase until approximately 2006 despite successful efforts to reduce the waste going in. In 1990, most landfills had no more than 15 years worth of waste. Therefore, as new waste is added between 1990 and 2006, no waste is being "retired" and any additional waste simply increases total WIP. Waste reduction efforts after 2006 do have an impact because, by this time, waste is being retired from methanogenic activity.

[14] The model developed to estimate WIP discounts waste deposited in town dumps through the 1970s because this waste's level of methanogenic activity is uncertain and there is no basis for assuming that the model used to estimate methane emissions accurately estimates methane from waste placed in town dumps.

Chart 2 - Estimated and projected waste-in-place in Missouri landfills, 1990-2015



In addition to an estimate of total WIP, the AAERL/OAR model requires an estimate of the distribution of WIP between small and large landfills. The 1990 Inventory assumed approximately 81 percent of total Missouri WIP was in 17 sanitary landfills qualified as "large" landfills within the AAERL/OAR model, that is, holding at least 1.1 million tons of waste-in-place. Taking this as a starting point, the projection assumes that the number of large landfills will increase to 20 and that after 1990, the percentage of WIP going to large landfills will increase from about 81 percent to about 90 percent. Table 21 summarizes the projected distribution of WIP between large and small landfills.

Table 21 - Projected distribution of WIP between large and small landfills

Units: 1,000 Short Tons

	1990	1995	2000	2005	2010	2015
High-WIP scenario						
Large landfills	84,071	94,341	100,203	105,716	103,986	102,114
Small landfills	19,720	21,885	22,478	22,406	20,051	17,484
Total	103,791	116,226	122,681	128,122	124,037	119,598
Low-WIP scenario						
Large landfills	56,517	71,569	82,987	93,437	92,986	88,565
Small landfills	13,257	16,543	18,491	19,840	18,216	15,552

Step 2: Application of USEPA methodology to estimate methane production

Equations 1 and 2, which are derived from the AAERL and OAR studies discussed previously, are prescribed by the USEPA *States Workbook* to estimate the generation of total statewide methane (CH_4) emissions from large landfills.

Equation 1 — CH_4 emissions from large landfills, high estimate

$$E_{large\text{-}high} = 1.15\ (C_{large}\ W_{landfill}\ P + 419{,}000\ N_{large})$$

Equation 2 — CH_4 emissions from large landfills, low estimate

$$E_{large\text{-}low} = .85\ (C_{large}\ W_{landfill}\ P + 419{,}000\ N_{large})$$

Where:

- C_{large} = emissions factor (cubic feet of CH_4 per ton of waste per day) for large landfills, estimated at .26 ft^3/ton/day

- W = total waste-in-place, defined as total quantity of waste that has been landfilled over the previous 30 years

- P = fraction of WIP placed in large landfills

- N_{large} = number of large landfills, defined as those with at least 1.1 million tons of waste-in-place

The USEPA methodology for estimating total statewide CH_4 emissions from small landfills and industrial landfills is simpler. Methane generation in small landfills is estimated by applying an emissions factor of .26 ft^3/ton/day estimated tons of WIP in small landfills. High and low estimates are based on an uncertainty factor of ±20 percent.

Methane generation from industrial landfills is estimated as the sum of 7 percent of emissions from large landfills (±15 percent) and of 7 percent of emissions from small landfills (±20 percent).

The result of these procedures is an estimate of methane generation. Net emissions are estimated by discounting these estimates of methane generation to account for oxidation, flaring and recovery. Oxidation is estimated by assuming an oxidation rate of 10 percent, but flaring and recovery must be estimated independent of the model.

This study assumes that flaring and recovery at Missouri landfills remains constant at the 1990 level until the year 2000. The 1990 level is documented in the *1990 Inventory.* After the year 2000, this study assumes a substantial increase in flaring and recovery due to the impact of new federal and state regulations that require certain landfills to develop landfill gas collection systems.[15] The estimate of flaring and recovery after the year 2000 assumes that the landfills required to establish methane collection systems produce 48 percent of the total landfill methane in Missouri[16] and that the average recovery efficiency of the methane collection systems equals 85 percent.[17]

Table 22 summarizes the resulting trend estimates for net methane emissions from Missouri landfills between 1990 and 1996, and Table 23 summarizes projections through 2015. The range of uncertainty reported in Tables 22 and 23 has two sources: uncertainty about the projected quantity of WIP in Missouri landfills and uncertainty deriving from Equations 1 and 2. The low estimate for each year is based on assuming the low WIP scenario, subtracting 15 percent from the emissions estimates for large landfills and subtracting 20 percent from emissions estimates for small landfills. The high estimate is based on assuming the high WIP scenario, adding 15 percent to the emissions estimates for large landfills and adding 20 percent to emissions estimates for small landfills. The "midrange" estimate is the average of the low and high estimate for the year.

Table 22 - Trend estimates of net methane emissions from Missouri landfills, 1990-96

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

	1990	1991	1992	1993	1994	1995	1996
Low estimate	3,906	4,113	4,266	4,412	4,549	4,678	4,800
High estimate	7,374	7,660	7,788	7,905	8,008	8,097	8,173
Midrange	5,501	5,748	5,895	6,032	6,158	6,273	6,378

[15] *Federal Register*, Vol. 61, No. 49, p. 9905, March 12, 1996. The Missouri Air Pollution Control Program is publishing regulations for St. Louis and the remainder of the state that affect some landfills not covered by the federal regulation. The regulations are intended to control nonmethane organic compounds (NMOCs) but the systems to collect and dispose of NMOCs are expected to remove methane as well; USEPA, *Greenhouse Gas Emissions from Municipal Waste Management, Draft Working Paper,* March 1997, Chapter 7.

[16] Personal communication, Paul Myers, Missouri Air Pollution Control Program, June 12, 1997.

[17] USEPA, *Greenhouse Gas Emissions from Municipal Waste Management, p. 100.*

Table 23 - Projected net methane emissions from Missouri landfills, 1990-2015

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

	1990	1995	2000	2005	2010	2015
Low estimate	3,906	4,678	3,803	4,131	4,037	3,792
High estimate	7,374	8,097	6,187	6,368	6,130	5,871
Midrange	5,501	6,273	4,930	5,205	5,046	4,788

These projections indicate that methane recovery and flaring will not have much effect on net CH_4 emissions from Missouri landfills prior to the year 2000 but will lead to a major reduction after 2000. Regardless of the accuracy of the specific projections in Table 23, it is likely that net methane emissions will peak in the year 1999, decrease to below 1990 levels in the year 2000, gradually increase again until 2006, and then decrease through 2015. However, as was pointed out at the beginning of the section on landfill methane emissions, this pattern could be affected by landfill operators' response to the federal and state regulations or to opportunities to invest in methane capture. Chart 3, which illustrates the magnitude of the effect of these regulations, assumes that landfill operators will invest in flaring and capture only to the extent required by law.

Chart 3 - Estimates of Missouri landfill methane emissions, 1990-2015

Section 2: Methane emissions from livestock

The *1990 Inventory* identified beef, dairy and swine operations as the leading sources of Missouri methane emissions in 1990. The *Inventory* estimated that methane emissions from Missouri beef and dairy cattle operations, swine operations and other livestock totaled nearly 10 million tons (STCDE) in the 1990 baseline year.

The *Inventory* found that cattle and swine operations accounted for nearly all methane emissions from livestock in Missouri. Therefore, this study estimates trends and projections only for cattle and swine. For other livestock — sheep, goats, horses, mules and poultry — the study assumes that methane emissions remain constant at the level estimated in the *1990 Inventory*.

The *Inventory,* following the *State Workbook,* identified two biological processes through which livestock operations lead to the emission of methane enteric fermentation in livestock digestive systems and anaerobic decomposition of livestock manure. The *Inventory* estimated that in the baseline year 97 percent of methane emissions from livestock digestive systems originated from cattle, with beef cattle accounting for 84 percent of all methane from enteric fermentation and dairy cattle accounting for another 13 percent. Similarly, the *Inventory* estimated that in 1990 swine and dairy operations together accounted for about 97 percent of emissions from manure management systems. Swine operations accounted for 64 percent of all methane emitted from decomposition of manure, and dairy operations accounted for another 33 percent.

This study estimates cattle and swine methane emissions trends through 1996 and emissions projections through 2015 using emissions factors developed in the *1990 Inventory*.

Enteric fermentation occurs during digestion when microbes that reside in animal digestive systems break down feed consumed by the animal. The amount of methane produced by an individual animal depends upon its digestive system and the amount and type of feed it consumes. Ruminants such as cattle have the highest methane emissions among all animal types because a significant amount of methane-producing fermentation occurs in their fore-stomachs. Although sheep and goats are also ruminants, they accounted for less than 1 percent of methane emissions from livestock digestive systems in 1990.

The decomposition of livestock manure produces methane when micro-organisms metabolize organic material in the manure. Under anaerobic conditions, the organic material is decomposed by anaerobic and facultative (living in the presence or absence of oxygen) bacteria. The end products of anaerobic decomposition are methane, carbon dioxide and stabilized organic material. Most of the methane emissions from manure management systems in Missouri come from swine and dairy operations because they rely heavily on anaerobic lagoons to dispose of manure. Anaerobic lagoons generate close to the maximum methane potential of the waste. Other livestock systems, including that of beef cattle, are managed using “dry” systems that promote conditions that limit methane production.

The emissions factors used to estimate cattle emissions through 1996 and swine emissions through 2015 were developed from methodology in the *State Workbook* and are summarized in Table 26 and Table 27. The *State Workbook* methodology for estimating methane emissions from enteric fermentation in cattle requires animal estimates for nine different categories of cattle, and the methodology for estimating emissions from manure management requires animal estimates for six different categories of cattle as well as two categories of swine.

The *1990 Inventory* provides a detailed explanation of the methodology used for the historic and trend estimates. In brief, the *Inventory* methodology for estimating emissions from enteric fermentation is based on regional emissions factors for six different categories of beef cattle and three different categories of dairy cattle. The emissions factors were developed using a model of rumen digestion and methane production for cattle feeding systems in the U.S. According to the *Workbook*, this model has been validated for a wide range of feeding conditions.

Similarly, the *Inventory* methodology for estimating emissions from manure management uses a weighted emissions factor for each livestock category, including three dairy categories and three beef categories. The livestock categories and emissions factors used in this study are identical to those used in the *Inventory*. As the *Inventory* explains in greater detail, the model used to estimate emissions is based on four factors — the typical animal mass for each livestock category, the "volatile solids" produced per year for each category, the "maximum methane producing capacity" of a pound of volatile solids for each category, and the potential of manure management systems to produce methane. The emissions factor for each livestock category is weighted to reflect the mix of management systems used to manage manure for that category.

Table 24 summarizes the emissions trends estimated by applying these methods. The total estimated emissions from livestock operations increased by nearly a million tons between 1990 and 1996, with increases in emissions from swine and beef cattle operations offsetting decreases from dairy cattle operations.

Table 24 - Estimated methane emissions from Missouri livestock operations, 1990-96

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

	1990	1991	1992	1993	1994	1995	1996
Beef cattle operations	5,677	5,634	5,772	5,933	6,288	5,956	6,161
Dairy cattle operations	1,808	1,766	1,701	1,686	1,605	1,552	1,477
Swine operations	2,747	2,623	2,705	2,946	3,321	3,401	3,296
Other livestock operations	170	170	170	170	170	170	170
Total	***10,402***	***10,194***	***10,349***	***10,735***	***11,384***	***11,079***	***11,105***

Projections of methane emissions from swine was based on these models because they required projecting only 1 to 2 categories of swine. However, projections of methane emissions from cattle could not be based on these models because they required projecting animal numbers in multiple categories and because there was insufficient data to make these projections. Rather, beef and dairy emissions were projected on the assumption that emissions would grow at the same rate as the total beef or dairy cattle population. Thus, the projections assume that the relative proportion of the different cattle categories will remain constant after 1996.

In addition, the projections of emissions from manure management assume that Missouri swine and dairy operations will continue to rely on anaerobic lagoons at the level at which they were used in 1990. The *State Workbook* estimates that in 1990 anaerobic lagoons were used for manure management in 80 percent of Missouri swine operations, compared to a U.S. average of 29 percent, and in 60 percent of Missouri dairy operations, compared to a U.S. average of 11 percent.

Table 25 summarizes projections of methane emissions from cattle, swine and other livestock. Total estimated emissions from livestock operations are projected to decrease by about 500,000 tons between 1996 and 2015, with emissions decreases from dairy operations partially offset by increases from swine operations. Emissions from beef operations are projected to remain stable throughout the period, with projected emissions for 2015 nearly identical to estimated emissions in 1995 and only slightly lower than estimates for 1996.

Table 25 - Projected methane emissions from Missouri livestock operations, 1990-2015

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

	1990	1995	2000	2005	2010	2015
Beef cattle	5,677	5,956	5,736	5,971	5,901	5,910
Dairy cattle	1,808	1,552	1,238	1,023	865	731
Swine	2,747	3,401	3,378	3,572	3,766	4,006
Other livestock	170	170	170	170	170	170
Total	***10,402***	***11,079***	***10,522***	***10,736***	***10,702***	***10,817***

Table 26 - Multipliers for methane emissions from enteric fermentation in cattle and swine

		Multiplier (tons / yr)
Dairy cattle		
E1	Replacements 0-12 months age	0.02080
E2	Replacements 12-24 months age	0.06315
E3	Mature cows	0.12035
Beef cattle		
E4	Replacements 0-12 months age	0.02240
E5	Replacements 12-24 months age	0.06690
E6	Mature cows	0.06545
E7	Weanling steer/heifer	0.02485
E8	Yearling steer/heifer	0.05170
E9	Bulls	0.11000
Swine		0.00165

Table 27 - Multipliers for methane emissions from cattle and swine manure

	Weighted Emissions Coefficient (tons per animal)	Weighted Emissions Coefficient (tons per 1,000 animals)
Cattle - mature dairy	0.18732	187.32
Cattle - mature non-dairy		
Female beef cows	0.00304	3.04
Male - Breeding bulls	0.00438	4.38
Cattle - young		
Pre-weaned calves	0.00110	1.10
Growing	0.00219	2.19
Feedlot-fed	0.00492	4.92
Swine		
Market	0.02398	23.98
Breeding	0.12363	123.63

Section 3: Methane emissions from cattle

Table 28 summarizes trend estimates for methane emissions from Missouri cattle operations. Emissions from cattle remained nearly stable between 1990 and 1996, with increases in emissions from beef operations offsetting decreases in emissions from dairy operations. Emissions are projected to decline by about a half million tons through 1990 and then remain nearly stable through 2015, with increases in emissions from beef continuing to offset decreases from dairy.

The primary determinant of emissions from cattle is historic. Projected numbers of beef and dairy cattle in Missouri are summarized in Table 30 for the years 1986 through 2015.[18] As Charts 4 and 5 indicate, the projected growth in Missouri beef cattle numbers is somewhat more optimistic than that for the U.S. in general, whereas the projection for Missouri dairy cattle numbers indicates a steeper drop than for U.S. dairy cattle in general.

Table 28 - Estimated methane emissions from Missouri cattle, 1990-96

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

	1990	1991	1992	1993	1994	1995	1996
Beef	5,677	5,634	5,772	5,933	6,288	5,956	6,161
Dairy	1,808	1,766	1,701	1,686	1,605	1,552	1,477
Total	***7,485***	***7,401***	***7,474***	***7,619***	***7,893***	***7,508***	***7,638***

Table 29 - Projected methane emissions from Missouri cattle, 1990-2015

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

	1990	1995	2000	2005	2010	2015
Beef	5,677	5,956	5,636	6,074	6,210	6,420
Dairy	1,808	1,552	1,238	1,023	852	700
Total	***7,485***	***7,508***	***6,874***	***7,097***	***7,062***	***7,120***

[18] Historic numbers are taken from the 1990 to 1995 editions of Missouri Department of Agriculture, *Missouri Farm Facts.* Projections are extrapolated from national and state projections prepared by the Food and Agriculture Policy Research Institute (FAPRI).

Table 30 - Historic and projected growth rates of cattle population in Missouri beef and dairy operations, 1986-2015

Units: 1,000 Head

		Beef Growth		*Dairy Growth*	
	Missouri Historic & Projected Data	National Historic & Projected Data	Rate of Change	Missouri Historic & Projected Data	Rate of Change
1986	4,450	89,554		236	
1987	4,273	87,346	-2.5%	232	-1.7%
1988	4,074	85,189	-2.5%	230	-0.9%
1989	3,982	82,486	-3.2%	228	-0.9%
1990	3,974	81,631	-1.0%	223	-2.2%
1991	4,025	82,334	0.9%	213	-4.5%
1992	4,125	83,696	1.7%	208	-2.3%
1993	4,240	85,342	2.0%	209	0.5%
1994	4,455	87,316	2.3%	197	-5.7%
1995	4,225	89,127	2.1%	190	-3.6%
1996	4,285	89,967	0.9%	179	-5.8%
1997	4,200	87,891	-2.3%	171	-4.5%
1998	4,230	86,171	-2.0%	163	-4.7%
1999	4,236	84,677	-1.7%	156	-4.3%
2000	4,242	83,756	-1.1%	150	-3.8%
2001	4,248	83,703	-0.1%	144	-4.0%
2002	4,254	84,697	1.2%	138	-4.2%
2003	4,260	85,973	1.5%	133	-3.6%
2004	4,266	86,771	0.9%	128	-3.8%
2005	4,272	87,188	0.5%	124	-3.1%
2006	4,277	86,843	-0.4%	120	-3.2%
2007	4,283	86,086	-0.9%	116	-3.3%
2008	4,289	86,112	0.0%	112	-3.3%
2009	4,295	86,139	0.0%	108	-3.3%
2010	4,301	86,165	0.0%	105	-3.3%
2011	4,307	86,192	0.0%	101	-3.3%
2012	4,313	86,219	0.0%	98	-3.3%
2013	4,318	86,245	0.0%	95	-3.3%
2014	4,324	86,272	0.0%	92	-3.3%
2015	4,330	86,299	0.0%	89	-3.3%

Chart 4 - Historic and projected Missouri beef cattle numbers compared to U.S. beef cattle history and projections, through 2015

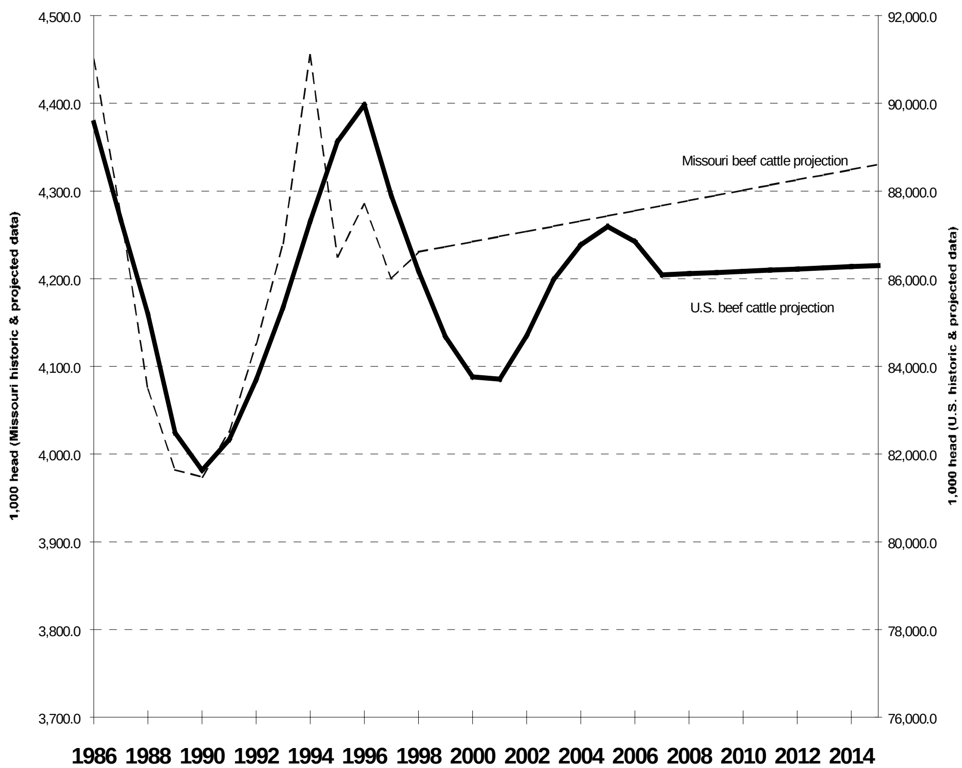
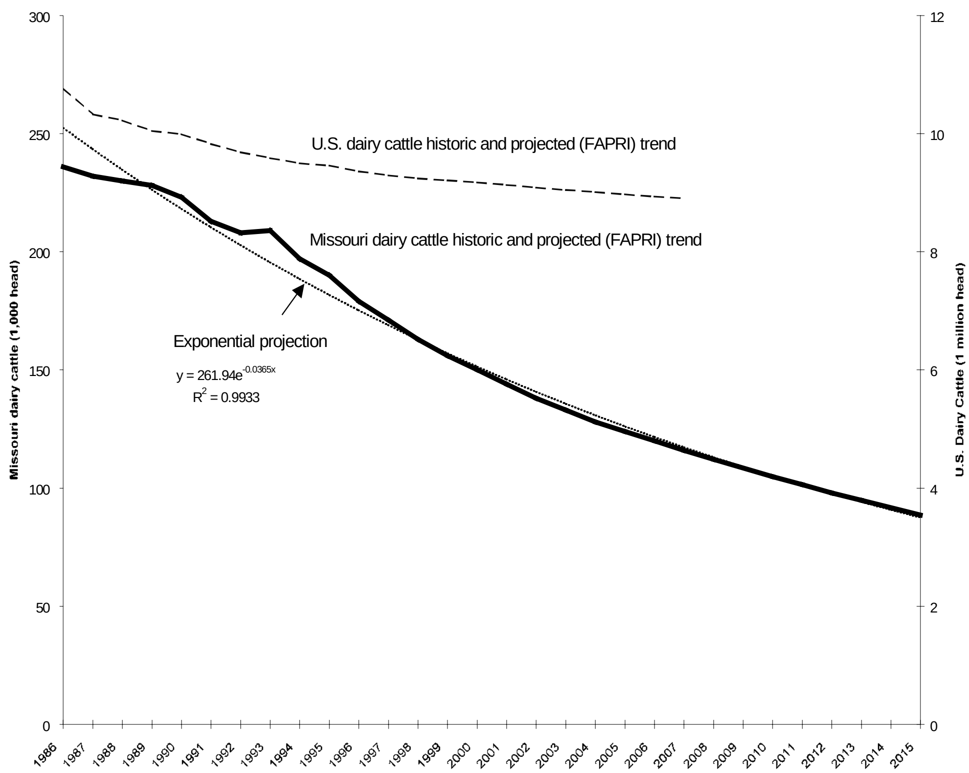


Chart 5 - Historic and projected Missouri dairy cattle numbers compared to U.S. dairy cattle history and projections, through 2015



The following worksheets summarize the steps taken to estimate historic and projected methane emissions from cattle operations in Missouri.

Table 31 - Worksheet for estimating methane emissions from enteric fermentation in Missouri beef and dairy cattle operations, based on animal population estimates, 1990-96

Estimated cattle population (1,000 animals) based on enteric fermentation categories

	E1 Dairy rplcmts 1-year	E2 Dairy rplcmts 2-year	E3 Mature dairy cows	E4 Beef rplcmts 1-year	E5 Beef rplcmts 2-year	E6 Mature beef cows	E7 Weanling steers & heifers	E8 Yearling steers & heifers	E9 Mature bulls	*Total Number of Animals*
1990	51	51	226	150	150	1,964	849	849	110	***4,400***
1991	53	53	220	173	173	1,960	805	805	110	***4,350***
1992	58	58	210	160	160	2,030	833	833	110	***4,450***
1993	50	50	210	175	175	2,060	855	855	120	***4,550***
1994	48	48	200	190	190	2,230	860	860	125	***4,750***
1995	40	40	195	183	183	2,105	818	818	120	***4,500***
1996	40	40	185	173	173	2,165	875	875	125	***4,650***

Estimated methane emissions from enteric fermentation in cattle

	E1 Emissions (Tons CH_4)	E2 Emissions (Tons CH_4)	E3 Emissions (Tons CH_4)	E4 Emissions (Tons CH_4)	E5 Emissions (Tons CH_4)	E6 Emissions (Tons CH_4)	E7 Emissions (Tons CH_4)	E8 Emissions (Tons CH_4)	E9 Emissions (Tons CH_4)	Enteric ferment'n (Tons CH_4)
1990	1,061	3,221	27,199	3,360	10,035	128,544	21,098	43,893	12,100	250,510
1991	1,092	3,315	26,477	3,864	11,540	128,282	20,004	41,619	12,100	248,293
1992	1,196	3,631	25,274	3,584	10,704	132,864	20,688	43,040	12,100	253,080
1993	1,040	3,158	25,274	3,920	11,708	134,827	21,247	44,204	13,200	258,576
1994	988	3,000	24,070	4,256	12,711	145,954	21,371	44,462	13,750	270,561
1995	832	2,526	23,468	4,088	12,209	137,772	20,315	42,265	13,200	256,675
1996	832	2,526	22,265	3,864	11,540	141,699	21,744	45,238	13,750	263,458

Table 32 - Worksheet for estimating methane emissions from manure management in Missouri beef and dairy cattle operations, based on animal population estimates, 1990-96

Estimated cattle population (1,000 animals) based on manure management categories

	M1 Mature dairy cows	M2 Mature beef cows	M3 Mature bulls	M4 Pre-weaned calves	M5 Feedlot steers & heifers	M6 Growing steers & heifers	*Total Number of Animals*
1990	226	1,964	110	1,014	87	999	***4,400***
1991	220	1,960	110	990	86	984	***4,350***
1992	210	2,030	110	1,085	81	934	***4,450***
1993	210	2,060	120	1,080	86	994	***4,550***
1994	200	2,230	125	975	98	1,122	***4,750***
1995	195	2,105	120	960	90	1,030	***4,500***
1996	185	2,165	125	1,030	92	1,053	***4,650***

Estimated methane emissions from manure management in cattle

	M1 Emissions (Tons CH_4)	M2 Emissions (Tons CH_4)	M3 Emissions (Tons CH_4)	M4 Emissions (Tons CH_4)	M5 Emissions (Tons CH_4)	M6 Emissions (Tons CH_4)	Manure mgmt. (Tons CH_4)
1990	42,335	5,980	482	1,112	191	4,913	55,013
1991	41,211	5,968	482	1,086	188	4,840	53,775
1992	39,338	6,181	482	1,190	178	4,591	51,961
1993	39,338	6,272	526	1,185	190	4,885	52,396
1994	37,465	6,790	548	1,069	214	5,519	51,605
1995	36,528	6,409	526	1,053	197	5,066	49,780
1996	34,655	6,592	548	1,130	201	5,179	48,305

Table 33 - Estimated methane emissions and carbon dioxide equivalent (STCDE) from enteric fermentation and manure management in Missouri beef and dairy cattle operations, 1990-2015

	CH_4 from enteric ferment'n in beef cattle (Tons)	CH_4 from enteric ferment'n in dairy cattle (Tons)	CH_4 from manure mgmt. in beef cattle (Tons)	CH_4 from manure mgmt. in dairy cattle (Tons)	Total CO_2 from beef cattle (STCDE)	Total CO_2 from dairy cattle (STCDE)	CO_2 from enteric ferment'n in all cattle (STCDE)	CO_2 from manure mgmt. in all cattle (STCDE)	*Total CO_2 from all cattle operations (STCDE)*
1990	219,030	31,481	12,678	42,335	5,676,836	1,808,483	6,137,502	1,347,817	***7,485,320***
1991	217,409	30,884	12,564	41,211	5,634,343	1,766,340	6,083,188	1,317,495	***7,400,683***
1992	222,979	30,101	12,623	39,338	5,772,260	1,701,244	6,200,460	1,273,044	***7,473,504***
1993	229,105	29,471	13,058	39,338	5,932,993	1,685,818	6,335,106	1,283,705	***7,618,811***
1994	242,504	28,058	14,140	37,465	6,287,777	1,605,297	6,628,748	1,264,326	***7,893,073***
1995	229,849	26,826	13,252	36,528	5,955,967	1,552,181	6,288,547	1,219,601	***7,508,148***
1996	237,835	25,623	13,650	34,655	6,161,387	1,476,801	6,454,709	1,183,479	***7,638,188***
1997	232,347	24,478	13,336	33,106	6,019,233	1,410,798	6,292,214	1,137,817	***7,430,031***
1998	227,799	23,332	13,074	31,557	5,901,393	1,344,796	6,152,715	1,093,475	***7,246,190***
1999	223,850	22,330	12,848	30,202	5,799,100	1,287,044	6,031,424	1,054,720	***7,086,144***
2000	221,415	21,472	12,708	29,040	5,736,014	1,237,543	5,950,721	1,022,836	***6,973,557***
2001	221,276	20,613	12,700	27,879	5,732,426	1,188,041	5,926,286	994,181	***6,920,467***
2002	223,903	19,754	12,851	26,717	5,800,470	1,138,539	5,969,594	969,415	***6,939,009***
2003	227,277	19,038	13,045	25,749	5,887,889	1,097,288	6,034,733	950,444	***6,985,177***
2004	229,385	18,322	13,165	24,781	5,942,494	1,056,036	6,068,838	929,692	***6,998,530***
2005	230,488	17,750	13,229	24,007	5,971,068	1,023,035	6,081,834	912,270	***6,994,103***
2006	229,577	17,177	13,176	23,232	5,947,452	990,034	6,045,471	892,015	***6,937,486***
2007	227,574	16,605	13,062	22,458	5,895,570	957,033	5,982,377	870,225	***6,852,603***
2008	227,644	16,055	13,066	21,714	5,897,394	925,325	5,970,624	852,095	***6,822,719***
2009	227,715	15,523	13,070	20,994	5,899,218	894,667	5,959,317	834,568	***6,793,885***
2010	227,785	15,008	13,074	20,299	5,901,042	865,025	5,948,442	817,625	***6,766,067***
2011	227,856	14,511	13,078	19,626	5,902,866	836,366	5,937,984	801,247	***6,739,231***
2012	227,926	14,030	13,082	18,976	5,904,690	808,655	5,927,930	785,415	***6,713,345***
2013	227,996	13,565	13,086	18,347	5,906,514	781,863	5,918,266	770,111	***6,688,377***
2014	228,067	13,116	13,090	17,739	5,908,338	755,959	5,908,980	755,317	***6,664,296***
2015	228,137	12,681	13,094	17,152	5,910,162	730,913	5,900,058	741,016	***6,641,074***

Section 4: Methane emissions from swine

Missouri total swine population was divided into market and breeding swine to accommodate the methodology for estimating methane emissions from manure. Missouri swine population through 2006, total and by category, was projected assuming that the growth rate of Missouri swine would be equal to the growth rates projected by FAPRI for U.S. market and breeding swine. To project Missouri swine population through 2015, growth rates for 2007 to 2015 were projected from the FAPRI growth rates for 1996 to 2006 using least squares linear regression. The resulting projections, illustrated in Chart 6 and summarized in Table 35, indicate that by 2015 Missouri's swine population will approach 4.5 million head, the previous historic high achieved in 1979.

Chart 6 - Estimated historic and projected Missouri swine population, 1975-2015

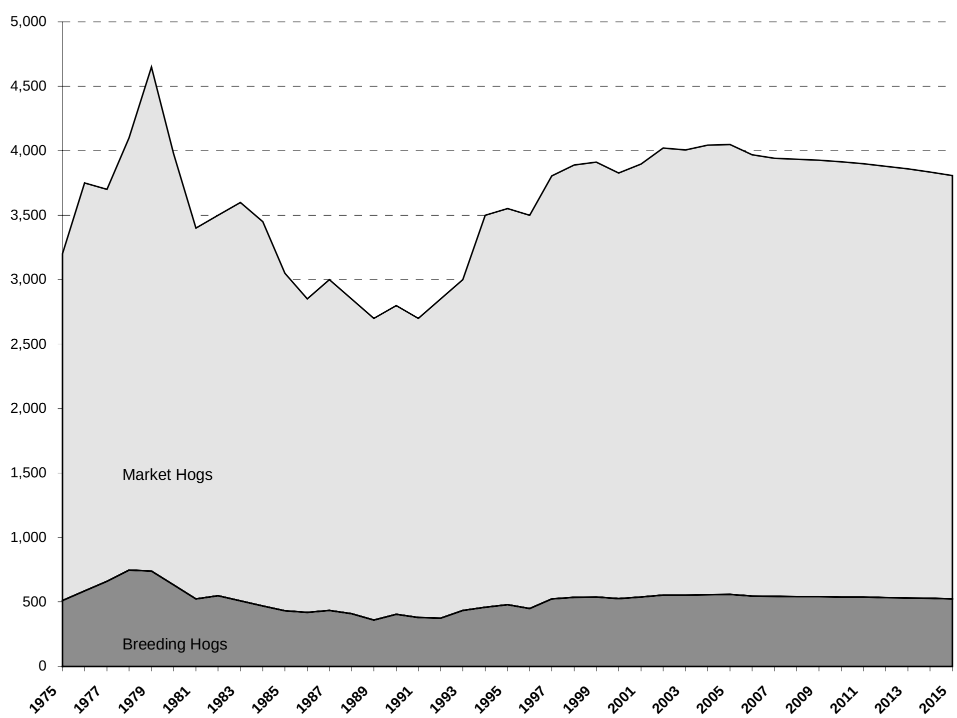


Table 34 - Estimated methane emissions from Missouri swine operations, 1990-96

	Enteric ferment'n (tons CH_4)	*Manure-breeding (tons CH_4)*	*Manure-other (tons CH_4)*	*Manure-total (tons CH_4)*	*Combined Emissions (tons CH_4)*	*Enteric ferment'n (equiv. tons CO_2)*	*Manure mgmt. (equiv. tons CO_2)*
1990	4,620	50,070	57,433	107,503	112,123.2	113,190	2,633,828
1991	4,455	46,980	55,634	102,614	107,068.9	109,148	2,514,040
1992	4,703	46,361	59,351	105,713	110,415.2	115,211	2,589,961
1993	4,950	53,779	61,509	115,289	120,238.7	121,275	2,824,574
1994	5,775	56,870	72,900	129,770	135,545.2	141,488	3,179,369
1995	5,858	59,343	73,620	132,962	138,819.7	143,509	3,257,573
1996	5,775	55,634	73,140	128,774	134,548.7	141,488	3,154,955
1997	6,277	64,869	78,640	143,509	149,785.8	153,779	3,515,973
1998	6,419	66,340	80,424	146,765	153,183.6	157,268	3,595,731
1999	6,455	66,708	80,870	147,578	154,033.1	158,140	3,615,670
2000	6,312	65,237	79,086	144,323	150,635.3	154,652	3,535,913
2001	6,431	66,463	80,573	147,036	153,466.8	157,559	3,602,377
2002	6,633	68,548	83,100	151,648	158,280.3	162,500	3,715,367
2003	6,609	68,302	82,803	151,105	157,714.0	161,919	3,702,074
2004	6,668	68,915	83,546	152,461	159,129.7	163,373	3,735,306
2005	6,680	69,038	83,695	152,733	159,412.9	163,663	3,741,953
2006	6,550	67,689	82,059	149,749	156,298.3	160,466	3,668,842
2007	6,502	67,199	81,465	148,664	155,165.7	159,303	3,642,256
2008	6,493	67,100	81,346	148,446	154,938.8	159,070	3,636,930
2009	6,478	66,947	81,160	148,107	154,585.1	158,707	3,628,628
2010	6,458	66,740	80,908	147,648	154,105.4	158,214	3,617,368
2011	6,432	66,478	80,591	147,068	153,500.8	157,594	3,603,176
2012	6,402	66,162	80,208	146,371	152,772.6	156,846	3,586,084
2013	6,366	65,794	79,762	145,556	151,922.6	155,973	3,566,131
2014	6,326	65,374	79,253	144,627	150,952.7	154,977	3,543,363
2015	6,280	64,903	78,682	143,585	149,865.1	153,861	3,517,834

Table 35 - Estimated and projected Missouri swine population, 1975-2015

Units: Number of Animals

	Total Swine	Breeding Swine	Other Swine
1975	3,200	512	2,688
1976	3,750	585	3,165
1977	3,700	660	3,040
1978	4,100	746	3,354
1979	4,650	739	3,911
1980	3,980	633	3,347
1981	3,400	525	2,875
1982	3,500	550	2,950
1983	3,600	510	3,090
1984	3,450	470	2,980
1985	3,050	430	2,620
1986	2,850	420	2,430
1987	3,000	435	2,565
1988	2,850	410	2,440
1989	2,700	360	2,340
1990	2,800	405	2,395
1991	2,700	380	2,320
1992	2,850	375	2,475
1993	3,000	435	2,565
1994	3,500	460	3,040
1995	3,550	480	3,070
1996	3,500	450	3,050
1997	3,804	525	3,279
1998	3,890	537	3,354
1999	3,912	540	3,372
2000	3,826	528	3,298
2001	3,898	538	3,360
2002	4,020	554	3,465
2003	4,005	552	3,453
2004	4,041	557	3,484
2005	4,049	558	3,490
2006	3,969	548	3,422
2007	3,941	544	3,397
2008	3,935	543	3,392
2009	3,926	542	3,384
2010	3,914	540	3,374
2011	3,898	538	3,361
2012	3,880	535	3,345
2013	3,858	532	3,326
2014	3,834	529	3,305
2015	3,806	525	3,281

Estimates of methane emission trends from swine operations, calculated by applying emissions factors summarized in Tables 36 and 37, are as follows:

Table 36 - Estimated methane emissions from Missouri swine, 1990-96

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

1990	1991	1992	1993	1994	1995	1996
2,747	2,623	2,705	2,946	3,321	3,401	3,296

Table 37 - Projected methane emissions from Missouri swine, 1990-2015

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

	1990	1995	2000	2005	2010	2015
	2,747	3,401	3,691	3,906	3,776	3,672
Average annual growth rate since 1990			***3.0%***	***2.4%***	***1.6%***	***1.2%***

Section 5: Methane emissions from other agricultural sources

In addition to livestock operations, the *1990 Inventory* identified rice cultivation and the burning of crop wastes as agricultural sources of methane emissions in Missouri. In 1990, rice cultivation contributed less than 1 percent of methane emissions from agriculture, and methane emissions from combustion of crop wastes was equivalent to less than 2 tons of carbon dioxide. Because these emissions constitute a very small fraction of all anthropogenic methane emissions in Missouri, this study assumes that emissions from these sources have remained constant since 1990.

Rice cultivation in southeast Missouri increased between 1990 and 1995, reaching a high of about 120,000 acres in 1995 compared to about 83,000 acres average in 1990. However, in 1996 the acreage decreased to about 90,000 acres, close to the 1990 level, in response to changes in subsidy requirements introduced by the 1995 farm bill. Future rice acreage is likely to remain fairly stable and is unlikely to exceed 120,000 acres.[19]

As the *1990 Inventory* points out, a number of factors besides planted acreage affect methane emissions from rice cultivation. The *Inventory* discusses several factors — such as the fact that Missouri rice fields are located farther north than the fields that served as the basis for developing the estimation methodology, and the relatively low use of organic fertilizer in Missouri rice fields — which suggest that actual methane emissions are at the lower end of the range estimated for the *1990 Inventory*. For these reasons, no attempt was made to estimate an increase in emissions due to the increase in Missouri's planted rice acreage.

[19]Personal communication, Bruce Beck, University of Missouri Extension Service, Poplar Bluff, September 17, 1997.

Part 3: Nitrous oxide emissions — trends and projections

The *1990 Inventory* estimated nitrous oxide (N_2O) emissions from several economic activities: use of nitrogenous fertilizers, burning of crop wastes, highway transportation and nitric acid production in Missouri. As discussed in the *1990 Inventory*, the processes leading to N_2O emissions are affected by multiple factors in addition to the level of the associated economic activity. Thus, estimates of nitrous oxide (N_2O) emissions are subject to higher uncertainty than estimates of methane emissions and much higher uncertainty than estimates of CO_2 emissions.

Because (1) N_2O emissions are a minor portion of Missouri greenhouse gas emissions, (2) estimates of N_2O are subject to a high degree of uncertainty and (3) resources for the analysis were limited, it was prudent to concentrate the analysis of N_2O emissions on the leading source, agricultural use of nitrogenous fertilizers. This source accounted for more than 60 percent of estimated 1990 N_2O emissions.

Tables 38 and 39 summarize trends and projections estimates for nitrous oxide emissions in Missouri. The estimates for N_2O emissions from fertilizer use are midpoint estimates. The estimates for other sources are assumed to remain constant at 1990 levels.

Table 38 - Estimated nitrous oxide emissions in Missouri, 1990-96

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

	1990	1991	1992	1993	1994	1995	1996
Total nitrous oxide emissions	3,805	3,859	3,925	4,001	3,877	3,855	3,820
Agriculture	2,333	2,388	2,454	2,530	2,406	2,383	2,348
Use of nitrogenous fertilizers	2,333	2,388	2,454	2,530	2,406	2,383	2,348
Disposal of crop wastes by burning	0	0	0	0	0	0	0
Highway transportation	1,080	1,080	1,080	1,080	1,080	1,080	1,080
Nitric acid production	391	391	391	391	391	391	391

Table 39 - Projected nitrous oxide emissions in Missouri, 1990-2015

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

	1990	1996	2000	2005	2010	2015
Total nitrous oxide emissions	3,805	3,820	3,875	3,872	3,870	3,868
Agriculture	2,333	2,348	2,403	2,401	2,399	2,397
Use of nitrogenous fertilizers	2,333	2,348	2,403	2,401	2,399	2,397
Disposal of crop wastes by burning	0	0	0	0	0	0
Highway transportation	1,080	1,080	1,080	1,080	1,080	1,080
Nitric acid production	391	391	391	391	391	391

Section 1: Nitrous oxide emissions from nitrogenous fertilizers

The *1990 Inventory* estimated that about 60 percent of Missouri's 1990 anthropogenic nitrous oxide (N_2O) emissions were due to the use of nitrogenous fertilizers. In 1990, between 700 and 14,000 tons of N_2O were released due to use of nitrogenous fertilizers, with a midpoint estimate of about 7,000 tons. The carbon dioxide equivalent of these emissions was between 219,000 and 4.5 million tons of CO_2, with a midpoint of about 2.3 million tons.

The wide range reflects the multiplicity of factors in addition to type and quantity of fertilizer that can affect N_2O emissions from this source. Nitrous oxide (N_2O) is produced from soil nitrogen through the microbial processes of denitrification and nitrification.[20] All other things being equal, an increase in the use of nitrogenous fertilizers leads to an increase in nitrogen in the soil and ultimately to an increase in the amount of N_2O emitted. However, as the *1990 Inventory* discusses, multiple factors affect the level of emissions. There is scientific consensus that numerous factors influence the biological processes of the soil micro-organisms that produce nitrous oxide emissions, but research has not been able to definitively establish the complex interaction of these factors.

Management factors that may affect emissions include the application technique, crop type, timing of application, tillage practices, use of other chemicals, irrigation and residual Nitrogen from crops or fertilizers. Current research suggests that high application rates for fertilizer, shallow placement of fertilizer, application in fall rather than spring, and no-till methods as opposed to tillage all may increase N_2O emissions.

Factors beyond managerial control that may affect emissions include temperature, precipitation, soil moisture content, availability of oxygen, porosity, pH, organic carbon content, thaw cycle, micro-organisms present and soil type. Experiments have shown that increases in pH, soil temperature, soil moisture, organic carbon content and oxygen supply may increase N_2O emissions.

Adopting the methodology of the *1990 Inventory*, this study estimates that N_2O emissions from use of nitrogenous fertilizers in Missouri increased by about 200,000 tons (midpoint STCDE) between 1990 and 1993, then decreased to about the 1990 emissions level between 1993 and 1996. These estimates are based on methodology from the *1990 Inventory.* The methodology estimates low, midpoint and high N_2O emissions by applying low, midpoint and high emissions coefficients to a three-year average of nitrogen fertilizer application.

Table 40 summarizes the data used to estimate emissions during 1990 and 1996. Data on annual application was derived from semi-annual reports of the Fertilizer Control Services (FCS) office of the Agricultural Experiment Station, University of Missouri-Columbia, on the shipment of fertilizers for use in Missouri. It is assumed that shipment for use provides a good estimate of actual fertilizer consumption.

[20] Denitrification is the process by which nitrates or nitrites are reduced by bacteria and which results in the escape of nitrogen into the air. Nitrification is the process by which bacteria and other micro-organisms oxidize ammonium salts to nitrites, and further oxidize nitrites to nitrates.

Table 40 - Worksheet for estimates of N_2O emissions from nitrogenous fertilizer use in Missouri, 1990-96

	Tons	*Tons*	*Tons*			*Tons*		
	Annual	**3-yr. ave.**	**Nitrogen Emitted**			**Nitrous Oxide Emissions**		
	N Applied	**N Applied**	**Low (C=.0011)**	**Midpoint (C=.0117)**	**High (C=.0224)**	**Low**	**Midpoint**	**High**
1989	418,524							
1990	378,953	396,608	436	4,640	8,884	686	7,292	13,961
1991	392,348	405,861	446	4,749	9,091	702	7,462	14,286
1992	446,281	417,098	459	4,880	9,343	721	7,669	14,682
1993	412,665	430,024	473	5,031	9,633	743	7,906	15,137
1994	431,126	408,929	450	4,784	9,160	707	7,518	14,394
1995	382,996	405,098	446	4,740	9,074	700	7,448	14,259
1996	401,172	399,161	439	4,670	8,941	690	7,339	14,050

Table 41 summarizes the resulting trend estimates. These estimates were derived by applying the Global Warming Factor (GWF) of 320 STCDE per ton of N_2O to the N_2O emissions estimates in the final three columns of Table 40. Summaries of greenhouse gas emissions appearing in other sections of this report use only the midpoint estimates.

Table 41 - Trend estimates for N_2O emissions from use of nitrogenous fertilizer in Missouri, 1990-96

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

	1990	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**
Low	219	224	231	238	226	224	221
Midpoint	2,333	2,388	2,454	2,530	2,406	2,383	2,348
High	4,467	4,572	4,698	4,844	4,606	4,563	4,496

N_2O emissions between 1990 and 2015 were projected by applying least-squares linear regression to the 1990 to 1996 emissions estimates. Based on this analysis, midpoint N_2O emissions between 1990 and 2015 will remain constant at about 2.4 million tons (midpoint STCDE), equivalent to a 0.1 percent growth rate in emissions between 1990 and 2015. Table 42 summarizes the resulting projections.

Table 42 - Estimated projections of N_2O emissions from use of nitrogenous fertilizer in Missouri, 1990-2015

Units: 1,000 Short Tons Carbon Dioxide Equivalent (STCDE)

	1990	1996	2000	2005	2010	2015
Low	219	221	226	226	226	225
Midpoint	2,333	2,348	2,403	2,401	2,399	2,397
High	4,467	4,496	4,601	4,597	4,593	4,589

Part 4: Perfluorinated carbon (PFC) emissions — trends and projections

Aluminum manufacture is the sole source of PFC emissions in Missouri. Two PFCs — tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6) — are emitted during the electrolytic reduction of alumina in the primary smelting process.[21] Although CF_4 and C_2F_6 are inert and therefore pose no health or local environmental problems, they are very potent greenhouse gases. To estimate the carbon dioxide equivalent of emissions of CF_4 and C_2F_6, this study uses the 1995 IPPC Global Warming Potential (GWP) factors. The GWP factor for CF_4 equals 6,300 STCDE per ton of PFC, and the GWP factor for C_2F_6 equals 12,500 STCDE per ton of PFC.

Noranda Aluminum, Missouri's only aluminum manufacturer, has joined in the Voluntary Aluminum Industry Partnership (VAIP) program sponsored by USEPA. Noranda provided this project with estimates of PFC emissions for 1990 to 1996 and projections for 2005 and 2015.[22]

PFCs are formed during disruptions of the production process known as anode effects, which are characterized by a sharp rise in voltage across the production vessel. The magnitude of emissions for a given level of production depends on the frequency and duration of the anode effects during that production period. The more frequent and long-lasting the anode effects, the greater the emissions. The estimates in Table 43 reflect Noranda's successful effort to reduce anode effects in its production process.

Table 43 - Noranda Aluminum estimates of PFC emissions in Missouri, 1990-2015

	Aluminum production (Metric tons)	CF_4 emissions (Metric tons)	C_2F_6 emissions (Metric tons)	CF_4 emissions (Short tons)	C_2F_6 emissions (Short tons)	CF_4 emissions (STCDE)	C_2F_6 emissions (STCDE)
1990	214,969	554	55	611	61	3,847	763
1991	216,140	172	17	190	19	1,194	237
1992	218,871	131	13	144	14	910	181
1993	219,640	139	14	153	15	965	192
1994	200,132	126	13	139	14	875	174
1995	217,773	128	13	141	14	889	176
1996	220,439	77	8	85	8	535	106
2005	250,000	55	6	61	6	382	76
2015	250,000	50	5	55	6	347	69

[21] Perfluorinated carbons are not emitted during the smelting of recycled aluminum.

[22] Communication from Dave Hart, Noranda Aluminum, April 16, 1997.